

Research Journal of Applied Sciences, Engineering and Technology 6(20): 3871-3878, 2013

ISSN: 2040-7459; e-ISSN: 2040-7467

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Submitted: January 22, 2013

Accepted: March 02, 2013

Published: November 10, 2013

Fuzzy Logic based Model to Predict Maximum Oil-Film Pressure in Journal Bearing

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Abstract: Oil-film pressure response is one of the key parameters that describe the operating conditions in hydrodynamic lubrication regimes. In the present study, a fuzzy logic model is developed to predict the maximum oil-film pressure in hydrodynamic plain journal bearing. In the development of predictive model, journal bearing parameters of rotational speed, bearing load and oil-feed pressure are considered as model independent variables. For this purpose, a number of experiments, based Box-Behnken experiment Design technique (BBD), are performed to observe the maximum oil-film pressure values. The results revealed that the model is able to predict maximum oil-film pressure adequately.

Keywords: Fuzzy logic, hydrodynamic lubrication, journal bearing, oil-film pressure

INTRODUCTION

Hydrodynamic journal bearings are typical critical power transmission components that carry high loads in different machines (Bouyer and Fillon, 2011). Therefore, it is essential to know the expected operating conditions of the bearings to gain high performance and avoid failure at the initial stage. The available predictive techniques for bearing analysis can be categorized into rigorous and rapid techniques (Campbell *et al.*, 1968; Martin, 1983; Majumdar, 1994). The use of numerical methods involves very detailed analysis of bearing geometry but tend to be expensive in skill and time and lack of accuracy in the determination of the overall performance of sliding bearings (Reddyhoff *et al.*, 2005; Mahieux, 2005; Podevin *et al.*, 2005; Arghir *et al.*, 2003; Sahlin *et al.*, 2005; De Kraker *et al.*, 2007; Rezaei *et al.*, 2009). Traditionally, the classic one-factor-at-a-time experimental approach had been applied to evaluate journal bearing behaviour by changing one variable while the other factors are constant. This technique is laborious and time consuming and seldom guarantees the determination of optimal conditions (Kasolang and Dwyer-Joyce, 2008; Survase *et al.*, 2006; Deligant *et al.*, 2011; Dimitrios and Pantelis, 2011).

The existing literature shows that most authors concerned with the study of the pressure of thin film by using the one-factor-at-a-time technique. Pawel (2011) has simulated the oil-film pressure distribution for laminar and steady oil flow in journal bearing. (Nuruzzaman *et al.*, 2010) have calculated the pressure

distribution and load capacity of journal bearing using finite element method. Their results were compared with analytical results. In another studies (Sharma and Pandey, 2009; Tsuneo, 2003; Valkonen *et al.*, 2010), experimental investigations were performed based on one-factor -at-a-time procedure to discuss the development of pressure profiles in the oil-film of slide journal bearing. These studies revealed that without considering the effects of other factors led to incorrect conclusions, due to the presence of interactions between the factors. In another study, (Stolarski, 2010), the inconsistency of the pressure profiles from experimental study with the theory results and has shown insufficient agreement.

These limitations of one-factor-at-a-time technique can be defeated by using Fuzzy Logic (FL) approach. FL as a predictive tool requires fewer rules and need fewer variables. The simplicity associated with the use of fuzzy logic allows for the researcher to circumvent the need for rigorous mathematical modeling. Modeling based on fuzzy logic is considered superior to modeling probability since probability only allows for considering stochastic uncertainty.

To the best knowledge of authors, no investigation is yet available in literature that addresses to the prediction of maximum oil-film pressure by fuzzy logic method. Thus, the aim of the present study is therefore to apply fuzzy logic approach to predict the maximum oil-film pressure in hydrodynamic journal bearing. The key process parameters taken into consideration are: speed (S), load (L) and oil-feed pressure (O). The solutions predicted by the developed model are compared with the actual values.

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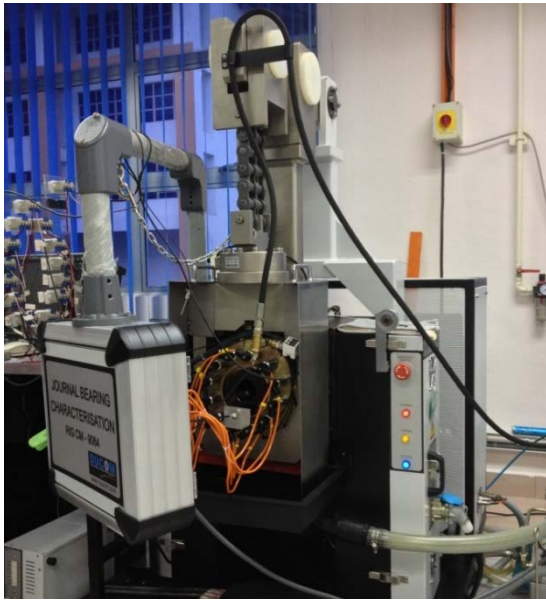


Fig. 1: Journal bearing test rig

MATERIALS AND METHODS

Journal bearing test rig: In this study a sturdy versatile journal bearing test rig CM-9064 (Fig. 1) was used to conduct the experiments. This test rig is easy to operate with provision to measure bearing friction, pressure and temperature profiles at different angular position on the circumference of journal bearing. The journal is mounted horizontally on a self-aligned bearings, it is rotated by a servo-motor with timing belt 2:1 pulley ratio. A centrifugally casted flawless bearing freely slides over journal with 100 microns clearance and as it rotates hydrodynamic bearing is formed.

The test rig consists of, a frame, bearing unit, loading, drive, lubrication, control and measuring systems. A Phosphorous bronze grade 1, centrifugally casted bearing having l/d ratio = 1 slides over journal with radial clearance of 0.05 mm. The inner surface of the bearing is ground and polished to surface finish of 1.6 Ra value with cylindrically and roundness below 3 microns (the inner diameter of the bearing 100.1 mm). The bearing part was modified to fix 12 pressure and temperature sensors on the front face and circumference of bearing at every 30° interval as shown in Fig. 2. The sensors use ultra stable technology that provides stability over a wide temperature range. The oil inlet and outlet temperatures were also measured using another two sensors as seen in Fig. 2.

A machined, ground and polished 100 mm journal is tightened to spindle by a draw bolt, the spindle is mounted inside housing rotating on taper roller bearing; the heat generated on spindle during test is cooled by



Fig. 2: Housing with pressure and temperature sensors. (1) Temperature sensor (2) Pressure sensor (3) Shaft (4) Temperature inlet (5) Temperature outlet

re-circulating oil from the lubrication unit (40 L). The oil to spindle is supplied from a 40 L capacity lube tank, fixed beside the tester, the oil is pumped by a gear pump and passed through a 50 microns high pressure filter before being supplied to housing through high pressure tubing, the oil enters at 3 points from the top of housing; the used oil, flows back to tank from the bottom of housing. The oil flow is constant at 6 lpm flow rate, the flow rate can be increased by operating the pressure regulator viewing the pressure gauge provided on lube tank. The oil feed-pressure ranges from 0.1 to 1 MPa.

The experiments were performed over a range of loads and speeds levels. The nominal load range of the bearing test rig is from 5 to 100 kN and the rotational speed range of the shaft is limited to 1000 rpm, due to the flow rate capacity of the test bearing lubrication system. The nominal output of the motor is 7.6 kW. The oil feed- pressure is regulated using a power pack lubrication system. Table 1 illustrates the details of test bearing dimensions, lubricant properties and operating parameters.

Design of Experiments (DOE): Of late, the Design of Experiment (DOE) is very widely employed in various science domains because of its benefits, such as, minimizing the number of experiments that are required to be accomplished, whereby, the laboratory works are considerably reduced (Ferreira *et al.*, 2007). The Box-

Table 1: Dimensions of test bearing, lubricant properties, operating parameters and sensor specifications

Part detail	Range
Bearing material	Phosphorous bronze
Inner bearing diameter D	100.1 mm
Bearing Length, L	50 mm
Surface roughness	0.8Ra on ID grounded and polished
Journal material	EN-353 steel
Outer journal Diameter, D	100 mm
	0.8Ra grounded and polished
	52 μ m (0.05 mm)
Surface roughness:	0.001
Radial clearance, c	5-100 kN
c/r ratio	100-1000 RPM
Load range, W	68 cSt @ 40°C
Journal speed	8.8 cSt @ 100°C
Lubricant viscosity	ISO VG 68
Lubricant	MEAS (M 5156)
Pressure sensor:	10 MPa
Model	(0.001 \pm 1% measured value) MPa
Range	
Accuracy	PT 100, make: Ajay sensor
Temperature sensor:	Max 200°C
Model	(1 \pm 1% measured temp.) °C
Range	
Accuracy	

Table 2: Process control parameters and their limits

Variables	Units	Notations	Factors Levels (coded)		
			-1	0	1
Speed	rpm	<i>S</i>	100	400	800
Load	KN	<i>L</i>	5	10	15
Oil-feed pressure	MPa	<i>O</i>	0.2	0.5	0.8

Behnken Design (BBD), as one of RSM design, was introduced just by employing three levels of each factor and consequently with an acceptable number of experimental points (Hinkelmann and Kempthorne, 2007). The employment the BBD should be constrained to a condition, in which one is not keen in estimating intense responses. Moreover, this design is rotatable (or near rotatable), which means that the model constitutes

Table 3: The BBD matrix with observed and predicted values of maximum oil-film pressure (MPa)

Run order	Coded factors			Experimental O^a (MPa)	Predicted by fuzzy
	<i>S</i> (rpm)	<i>L</i> (KN)	<i>O</i> (MPa)		
1	0	1	1	8.00	8.06
2	0	0	0	5.66	5.65
3	1	-1	0	3.29	3.25
4	1	0	-1	4.17	4.15
5	1	1	0	8.28	8.24
6	-1	0	1	6.23	6.20
7	0	-1	-1	2.96	3.10
8	-1	0	-1	5.63	5.50
9	1	0	1	5.47	5.46
10	0	0	0	6.11	5.96
11	0	1	-1	7.64	7.66
12	0	0	0	5.94	5.93
13	-1	-1	0	3.55	3.54
14	0	-1	1	3.21	3.20
15	-1	1	0	8.02	8.03

^aAverage of three readings

a rationally constant circulation of scaled forecast variation right through the experimental design region (Montgomery, 2005). It needs three levels of each factor, which results in minimized experimental testing to assess multiple variables and their interactions (Ragonese, 2002).

Depending on a three-level-three-factor Box–Behnken design, the experiments have been designed. The key process parameters for journal bearing that determine the maximum oil-film pressure are: rotational speed (*S*), bearing load (*L*) and oil-feed pressure (*O*). Three levels of each input variable are used in Box–Behnken design technique so that design the experimental design before executes the experimentation. Each experiment was replicated thrice. The manipulated variables and their levels investigated in this study are given in Table 2.

The experiment has been conducted based on the design matrix as given in Table 3,

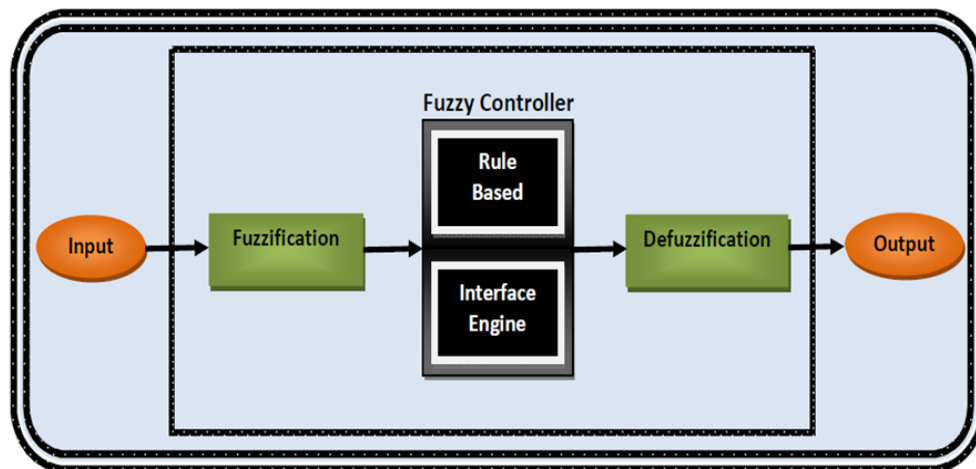


Fig. 3: Blocks of a fuzzy controller

in order to avoid any systematic error in the experiment. Total numbers of independent design points add to 15. The average of at least three results of maximum oil-film pressure are calculated and presented in Table 3. The experimental data were used as input of fuzzy logic to predict the maximum oil-film pressure.

Fuzzy logic approach: Fuzzy Logic (FL) was initiated first by Zadeh (1965, 1968, 1973), to manipulate and represent data and information possessing non-statistical uncertainties. FL was particularly introduced to mathematically represent uncertainty and vagueness and to provide formalized tools for dealing with the imprecision intrinsic to many problems. Essentially, FL uses the mathematical theory of fuzzy sets to mimic the process of human mind to effectively employ modes of reasoning by allowing the computer to behave less precisely and logically than conventional computer. Significant components that characterise the fuzzy controller, viz; input, fuzzification, rule based, membership functions, interface engine, defuzzification and output are shown in Fig. 3.

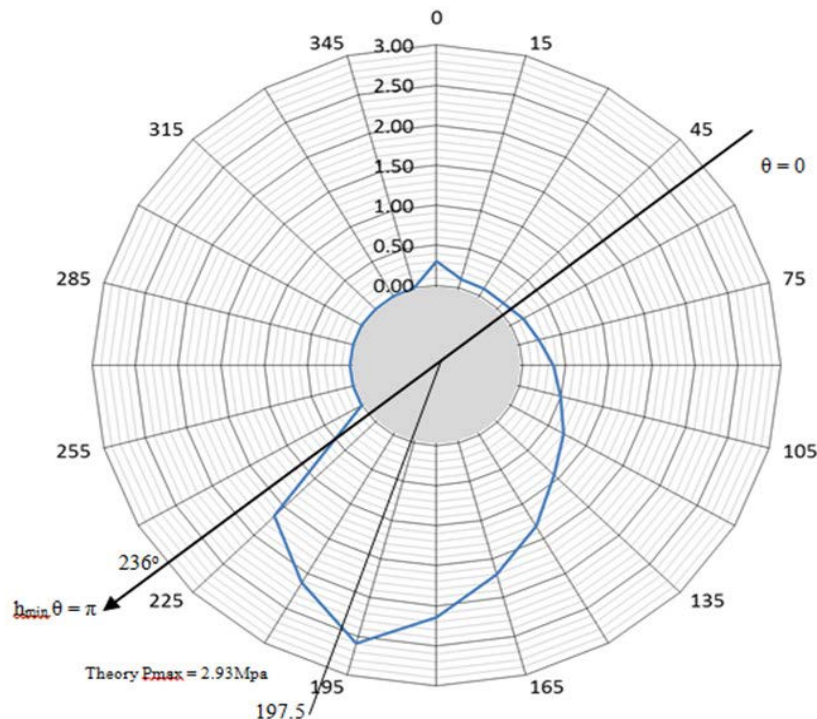
The basic concept underlying fuzzy logic is that of a linguistic variable, that is, a variable whose values are words rather than numbers. Although words are often less precise than numbers, their use is closer to human perception. It can be described simply as control with sentences rather than equations and it can include empirical rules that are especially useful in operator controlled plants. For instance a typical fuzzy controller

“If journal speed is (Medium) and load is (Low) and oil-feed pressure is (Low) then oil-film pressure is (Very Low)”. This sentence builds in the familiar if-then format and formally the if-side is called the condition and the then-side is called the conclusion. Linguistic variables such as low, medium and high can be included in the model without needing to be precisely defined. This is an essentially superior characteristic of fuzzy logic modeling as it permits for imprecise measurements. In general, fuzzy logic as a concept is easy to understand, because the mathematical aspects behind fuzzy reasoning are very simple.

RESULTS AND DISCUSSION

Experimental identification of max-pressure location: Pressure distribution around the hydrodynamic journal bearing circumference is experimentally determined. The aim of this step is to identify the region of interest (the maximum oil-film pressure location around the bearing circumference) so that to be modelled next stage. The lubricant pressure profile is measured by the 12 pressure sensors that are fixed on the front face bearing (Fig. 2). The pressure sensors measure the fluid pressure developed through the holes bored to within 0.5 mm, from the bearing surface.

Experimental results of oil-film pressure distribution at rotational speed of 600 rpm with different loads are plotted in Fig. 4. The theoretical



(a) At 6 kN load

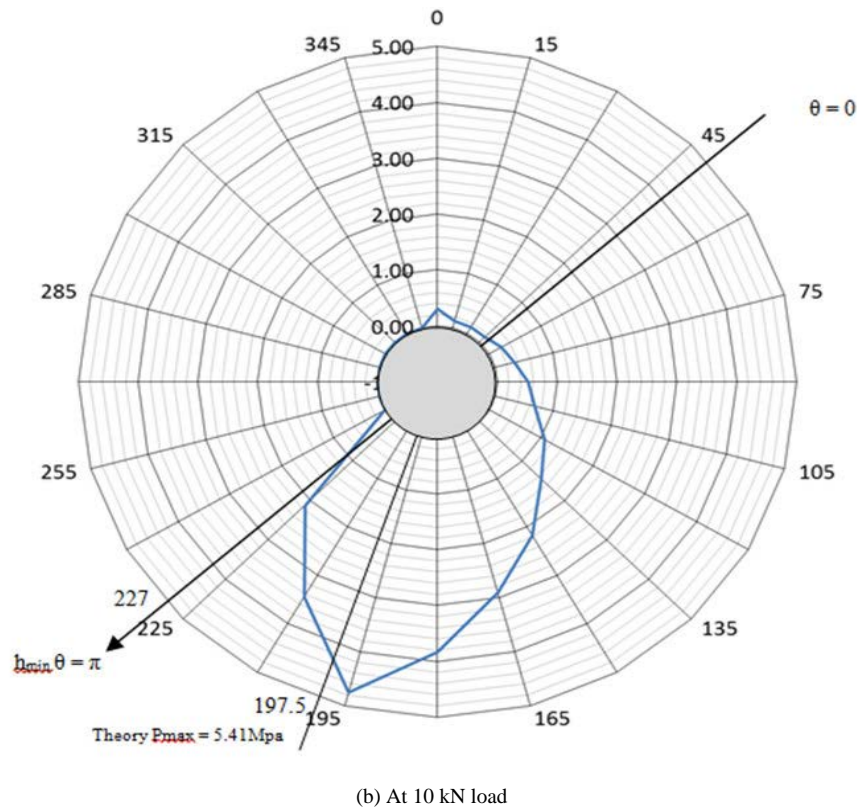


Fig. 4: Experimental pressure distribution around the journal bearing circumference

values obtained from charts of Raimondi and Boyd (1958) are also shown on the plotted profiles. For the same operating conditions in the test, the predicted maximum pressure location from Raimondi and Boyd chart is to be at 197.5° (Fig. 4a and b). This experiment has revealed that the maximum pressure position was recorded at 195° . The experimental values nearly agree with the predicted values from (Raimondi and Boyd, 1958).

Therefore in this study, the modeled region is particularly determined to be particularly at 195° which equivalents to the pressure sensor no. 7 located on the front face of the true scale bearing circumference (Fig. 2). Theoretically, when the load increases, the position of film thickness will shift to a new position. However, the position of maximum pressure remains the same as predicted from chart of (Raimondi and Boyd, 1958). Conventionally, the converging and diverging sections are defined by the minimum film thickness. In diverging section the pressure may drop to sub-atmospheric pressure (Desai and Patel, 2005). However, in this study, values of zero are assumed in this diverging section.

Proposed fuzzy sets structure: The fuzzy model that has been designed to predict the maximum oil-film

pressure in hydrodynamic journal bearing uses three inputs obtained from Box-Behnken design and one output. Rotational speed, bearing load and oil-feed pressure are the inputs and oil-film pressure is the output of the system. The first step in establishing the algorithm for selecting the lubrication condition is to choose the shape of fuzzy membership functions or fuzzy sets for the process variables based upon experimental data. The system is based on the interrelationship that exists for lubrication material between its speed (input 1), load (input 2), oil-feed pressure (input 3) and are distributed and triangle shape is used for the membership functions for the input and the output variables. The membership functions for each fuzzy set for input fuzzy variables and for output fuzzy variable are shown in Fig. 5 to 8, respectively. The predicted values of the maximum oil-film pressure by the proposed model are presented in Table 3.

- **Rule-based fuzzy relations:** Fuzzy rules are a set of linguistic statements which establishes the relationship between the input and the output in a fuzzy system. They are defined based on experimental work. The number of fuzzy rules in a fuzzy system is related to the number of fuzzy sets

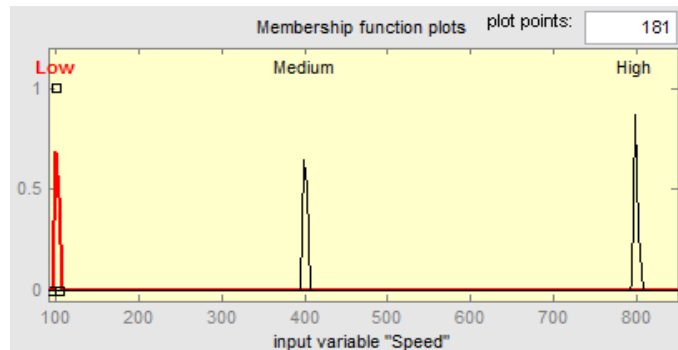


Fig. 5: Speed input membership function

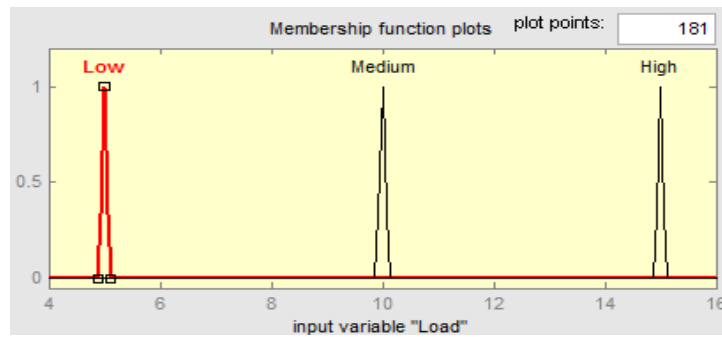


Fig. 6: Load input membership function

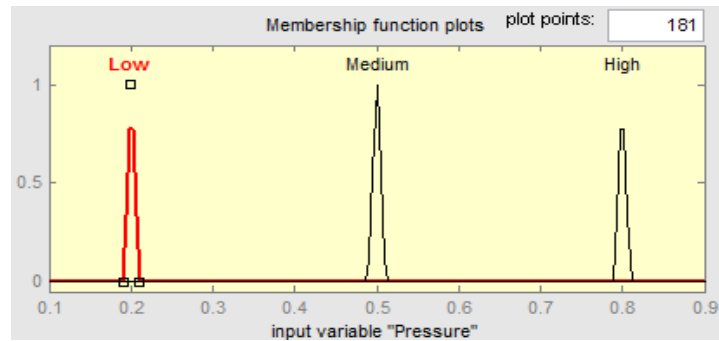


Fig. 7: Oil-feed pressure input membership function

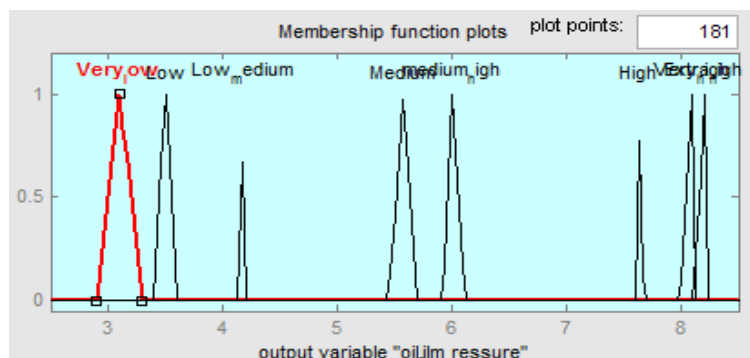


Fig. 8: Oil-film pressure output membership function

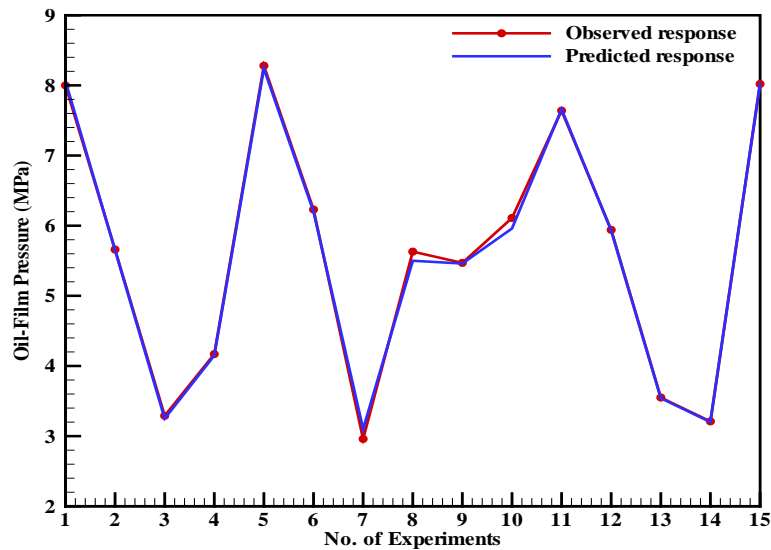


Fig. 9: Experimental data vs. predicted data by fuzzy logic

Table 4: Validation test results

Run no	S (rpm)	L (KN)	F (MPa)	Experimental	Fuzzy predicted	Error %
1	800	5	0.5	3.29	3.25	1.20
2	800	15	0.5	8.28	8.24	0.48
3	800	10	0.8	5.47	5.46	0.18

for each input variable. In this study, there are three input variables which are classified into fifteen fuzzy sets and there are fifteen total of oil-film pressure values to be determined. The “and” and “or” used in the rules will apply to the fuzzy “and” and “or” operations, respectively.

Verification test: In this study, FL approach was employed for predicting the maximum oil-film pressure in hydrodynamic journal bearing. At this stage, comparison criteria are needed to quantify the difference between the predicted values and the actual values. Three confirmation experiments of the observed and predicted values, that were randomly selected from the ranges illustrated in the Table 3 together with the residuals (the error percentage), are shown in Table 4. The residual is within permissible limits. Thus, from Table 4, it is obvious that FL is capable of predicting the oil-film pressure response values for any combination of the speed, load and oil-feed pressure values within the range of the experimentation conducted. In addition, Fig. 9 shows the distribution of maximum oil-film pressure of the actual values versus predicted values by fuzzy logic.

CONCLUSION

Fuzzy Logic (FL) had been employed to predict the desired response of maximum oil- film pressure in

hydrodynamic plain journal bearing. The results show that the application of a fuzzy logic based model for predicting maximum oil-film pressure is possible for the independent variables rotational speed, bearing load and oil-feed pressure and produce the best match between predicted and experimental data. Predicted values were compared with the experimental values and their closeness was determined. FL model is capable to predict the response with average percentage deviation of 1 or 99% accuracy. The results presented in this study are expected to be quite useful to the bearing designers as well as academic community.

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